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Terrestrial record of the Solar System's oscillation about the galactic plane

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Impact cratering on the Earth over the past 600 Myr has been partly sporadic, partly episodic. The episodic component is suspected to have been cyclical, with a mean period of ~32 Myr (refs 1, 2). According to a theory proposed to explain this phenomenon[1], gravitational encounters between the Solar System and interstellar clouds of intermediate to large size occasionally disturb the outer Solar System comets, with the consequence that some of these comets fall into the inner regions of the system, where a few hit the Earth. Because the episodes of impact cratering, however, are not precisely periodic[1,3], the galactic mechanism must be in part stochastic. The irregular part can be attributed to the randomness in the local space distribution of the interstellar clouds (and various other perturbing galactic objects[4]). The periodic component probably arises from the harmonic oscillation of the Sun about the galactic plane, since the large-scale space density of the interstellar clouds and other objects falls off with increasing distance from the plane. A new study of the observational evidence is presented here. Contrary to a claim by Thaddeus and Chanan[5], the vertical scale height of the clouds seems to be sufficiently small and the Sun's vertical trajectory sufficiently large for the modulating effect of the Sun's galactovertical motion to be detectable in the terrestrial record of impact cratering with at least a 50% *a priori* probability.

The Sun's past oscillations perpendicular to the galactic plane have probably always been confined within $|z| < 300$ pc, and so they have probably closely followed simple harmonic motion[6]. The present vertical amplitude, z_{max}, can be determined from the Sun's present height, $z_\odot$, its present velocity, $Z_\odot$, and the half-period of oscillation, $P_{1/2}$, by means of the relation

$$z_{max} = (z_\odot^2 + P_{1/2}^2 Z_\odot^2/\pi^2)^{1/2} \qquad (1)$$

The half-period (that is, the time elapsed between successive crossings of the galactic plane) follows from Poisson's equation as[6]

$$P_{1/2} = (\pi/4G\rho_0)^{1/2} \qquad (2)$$

where ρ_0 is the local mass density in the galactic plane and G is the gravitational constant.

The Sun's height above the Galaxy's mean plane is usually taken to be $z_\odot = 8 \pm 12$ pc from H I observations[7,8]. Molecular cloud observations confirm that $z_\odot \approx 0$ (ref. 9), but the observed distribution of young stars and star clusters puts the Sun at $z_\odot = 20$–30 pc (refs 7, 10, 11). The exact value of $z_\odot$ is not critical because the Sun moves through this region very quickly, so $z_\odot = 10 \pm 10$ pc will be adopted.

Table 1 Solar velocity (km s^{-1}) perpendicular to the galactic plane with respect to local interstellar material and young stars

Interstellar material			Young stars		
Objects	$Z_\odot$	Ref.	Objects	$Z_\odot$	Ref.
H I clouds	7.7	15	OB stars	6.3*	23
	8.5	16		6.9	24
	8.8	17		7.2*	25
	9.4	18		7.3*	26
	11.2	19		7.5*	12
	12.1*	20		7.7	27
				7.8	28
				9.1	22
Ca II clouds	8.2	21			
	9.3	22			
			Classical Cepheids	6.4	29
Molecular clouds	11.4*	12		7.3	30
	—			8.2	31
	—			10.0	32
	—			11.4	33
Gas and dust (mean)	9.6		Stars (mean)	7.9	

Solar motion solutions were based on observed radial velocities for the interstellar material and on observed radial velocities and proper motions for the young stars.

* An average of published solutions has been taken. For the O and B stars, only solutions for stars with distances $r \leq 1.3$ kpc have been used in forming the averages.

$Z_\odot$ is probably indistinguishable from the z component of the Sun's motion with respect to the local standard of rest (LSR). The LSR is most accurately determined from velocity observations of the local gas, dust and young stars, because these objects suffer relatively little selection bias in surveys, while they possess a strong concentration towards the galactic plane, have low random velocities with little or no systematic drift motion perpendicular to the galactic plane (either observationally[12] or theoretically[13,14]), and contribute a significant fraction of the local mass density[4]. Recently published values of $Z_\odot$ are listed in Table 1 (refs 12, 15-33). The apparent difference of 1.7 km s^{-1} between the mean values of $Z_\odot$ for young stars and diffuse matter probably has no significance because the ranges of $Z_\odot$ within the two groups of objects are very similar. All 22 values listed in Table 1 yield $\langle Z_\odot \rangle = 8.6 \pm 1$ km s^{-1} (estimated mean error). This exceeds by a moderate amount the commonly quoted estimates of 6-8 km s^{-1} (refs 8, 34, 35) which, although heavily weighted (40-100%) by young stars and diffuse matter, are based on data >25 yr old.

The vertical concentration of objects in the flat galactic subsystem can be determined by measuring their mean absolute height $\langle |z| \rangle$, r.m.s. height $\langle z^2 \rangle^{1/2}$, exponential scale height β, or gaussian dispersion σ, where β and σ are defined by

$$N(z) = N_0 \exp(-|z|/\beta) \qquad (3)$$

and

$$N(z) = N_0 \exp(-z^2/2\sigma^2) \qquad (4)$$

An exact exponential distribution will have $\beta = \langle |z| \rangle$ and $\langle z^2 \rangle^{1/2}/\langle |z| \rangle = 1.41$, whereas an exact gaussian distribution will have $\sigma = \langle z^2 \rangle^{1/2}$ and $\langle z^2 \rangle^{1/2}/\langle |z| \rangle = 1.25$. The gaussian half-width at half-maximum is $z_{1/2} = 1.18\sigma$.

Table 2 contains empirically determined values of $\langle |z| \rangle$, $\langle z^2 \rangle^{1/2}$, β and σ, adopted from 14 recently published studies for the solar neighbourhood[5,9,10,36-46]. All values that depended on kinematical distances obtained by the method of circular galactic rotation have been adjusted to fit a best-estimate solar galactocentric radius of $R_0 = 8.5 \pm 0.5$ kpc (refs 47, 48). Of necessity, classical Cepheids and H I clouds have been omitted from consideration because they exhibit a wider dispersion than do

Table 2 Characteristic galactic heights (pc) of local interstellar material and young stars

Object	$\langle\lvert z\rvert\rangle$	$\langle z^2\rangle^{1/2}$	β	σ	Ref.
H II regions	62	84	—	—	36
	—	85*	—	—	37
Molecular clouds	—	—	—	42*	38
	—	>53*	—	—	39
	—	—	—	54*	9
	—	—	—	61*	5
OB stars	—	—	—	45	40
	45	—	—	—	41
	50	—	—	—	42
	50	74	46	48	10
	54	—	—	—	43
	54	—	—	—	44
	57	82	—	—	36
Young star clusters	47	65	—	—	36
	53	—	—	—	45
	—	75	—	—	46
	63	79	68	61	10
Gas and dust (mean)	(62)	84	—	52	
Stars (mean)	53	75	57	51	

* Scaled to a solar galactocentric radius of $R_0 = 8.5$ pc.

the other objects. Since the young stars show $\beta/\langle\lvert z\rvert\rangle = 57/53 = 1.08$ and $\langle z^2\rangle^{1/2}/\langle\lvert z\rvert\rangle = 75/53 = 1.42$, an exponential distribution characterizes them very well. In the case of molecular clouds, values for σ alone have been published. However, as molecular clouds and young stars have formally nearly the same values of σ, it is reasonable to assume that both classes of objects (which are also genetically related) follow the same exponential distribution, at least in the solar neighbourhood where distances are well determined.

Potential sources of observational bias for the various objects used include: heavy interstellar obscuration (of the stars) near the galactic plane, accidental errors in the distances, and warping of the galactic plane. These effects tend to widen the apparent vertical distribution of the objects. Estimates of the actual amount of bias, however, have shown that it is very small[9,36]; the zero point error in the distances is probably also small[48]. A statistically corrected value of $\beta = 50 \pm 5$ pc will therefore be adopted.

$P_{1/2}$ can be determined from equation (2) through a knowledge of ρ_0. Direct counts of stars, gas and dust yield $\rho_0 = 0.10$–$0.11\ M_\odot\ \mathrm{pc}^{-3}$ (refs 49, 50). Dynamical analyses of stellar motions perpendicular to the galactic plane have produced best-estimate values covering the range 0.075–0.235 $M_\odot\ \mathrm{pc}^{-3}$ (14 values are listed by Krisciunas[51] and seven values come from other sources[49,50,52–56]). The mean of all 21 dynamically determined values is $0.145 \pm 0.01\ M_\odot\ \mathrm{pc}^{-3}$. However, the latest dynamical studies by Bahcall[50] have produced a modern series of allowed values covering the range 0.10–0.35 $M_\odot\ \mathrm{pc}^{-3}$, his best estimate being $0.185 \pm 0.02\ M_\odot\ \mathrm{pc}^{-3}$. I shall therefore adopt $0.18 \pm 0.04\ M_\odot\ \mathrm{pc}^{-3}$. This corresponds to $P_{1/2} = 31 \pm 3$ Myr and implies that almost half of the local matter is invisible.

Using the above results for $z_\odot$, $Z_\odot$ and $P_{1/2}$, equation (1) yields $z_{max} = 88 \pm 13$ pc. Consequently, z_{max}/β must be 1.8 ± 0.3, which is not significantly different from Rampino and Stothers's[1] assumed value of 1.6.

The Sun's orbital revolution around the galactic centre probably has had little direct effect on z_{max}/β. At present, the Sun lies very near the pericentre of its orbit, unless encounters with the most massive interstellar clouds and the Galaxy's spiral arms have significantly deflected its ballistic trajectory. If the LSR is taken to be also the local rotational standard of rest, the Sun passed the apocentre at $R \approx 1.14\ R_0$ (ref. 57). If, however, the LSR is moving outwards from the centre of the Galaxy at ~7 km s^{-1} (refs 58–61), the Sun's true orbit would be more nearly circular. Over short radial distances beyond the solar circle, β increases as $R^{1.5}$ according to published data compiled for OB stars, young star clusters and H II regions[36], but as $R^{0.5}$ according to published molecular cloud data[5,9]. Since ρ_0 decreases outward as $R^{-4\pm2}$, in typical models of the Galaxy that reproduce the observed surface-brightness distributions and rotation curves of galaxies that are morphologically similar to our Galaxy[62–65], $P_{1/2}$ probably increases outwards as $R^{2\pm1}$. Azimuthal variations in ρ_0 (refs 9, 39, 66, 67) and secular changes in β over the past 10^9 yr (ref. 68) appear to be small near the solar circle. Therefore, the part of z_{max}/β that is independent of $Z_\odot$ probably increases by $<\sim 15\%$ between the pericentre and apocentre of the Sun's orbit. As $P_{1/2}$ over the same range of distance probably increases by 0–30%, the time average of $P_{1/2}$ must have been close to 33 ± 3 Myr.

The Sun's average z velocity during the past 600 Myr is usually assumed to be constant. Note, however, that a close encounter of the Sun with a giant molecular cloud, although expected to be a very rare occurrence[69,70], could have significantly deflected the Sun's ballistic trajectory. The Sun's present r.m.s. z velocity averaged over a vertical orbit is $8.6/\sqrt{2} = 6.1\ \mathrm{km\ s}^{-1}$, which lies well below the ensemble mean for other solar-type stars, $\sim 20\ \mathrm{km\ s}^{-1}$ (ref. 71). A value of $20\ \mathrm{km\ s}^{-1}$ would produce $z_{max} \sim 300$ pc and $z_{max}/\beta \sim 6$. However, I shall adopt in the following calculations $z_{max}/\beta = 1.8$, as derived above for the unperturbed Sun.

Under the simplest assumptions, the rate at which the Sun encounters known as well as unknown objects belonging to the Galaxy's flat component will be proportional to f_0, the mass fraction of all flat-component material at $z = 0$ (ref. 4). Observations suggest that f_0 may be as low as 0.17 (and possibly even lower) or as high as 0.75. The largest known contributor to f_0 is interstellar clouds[9,50]. An improved assumption in this situation is obviously to set the rate of encounters proportional to the relative perturbing influence of interstellar clouds (compared with other galactic objects) on the Sun's halo of comets. However, an 'effective' fraction f of this kind is much harder to estimate than f_0, although obviously $f > f_0$, since the partial breakdown of the impulse approximation for a close encounter between an interstellar cloud and the Sun's cometary system implies an enhanced gravitational perturbation[70,72–74].

The rate of solar encounters with interstellar clouds will also depend on the relative velocity of the encounter. The component of the Sun's peculiar velocity that lies in the direction parallel to the galactic plane is $\sim 20\ \mathrm{km\ s}^{-1}$, and so the Sun's peculiar velocity is expected to change over a vertical orbit by only ~10%, an amount which can be neglected. Therefore, the rate r_i of solar encounters with objects having a scale height β_i and an effective fractional mass density in the plane f_i can be taken to be[1,4]

$$r_i = Cf_i \exp\left[-(z_{max}/\beta_i)\sin(\pi\phi)\right] \tag{5}$$

where $\phi = t/P_{1/2}$ and C is the constant part of the encounter cross-section. Over a vertical orbit, the fraction of encounters that occur in the phase interval ϕ_1–ϕ_2 is then

$$n/N = \sum_i \int_{\phi_1}^{\phi_2} r_i\, \mathrm{d}\phi \Big/ \sum_i \int_0^1 r_i\, \mathrm{d}\phi \tag{6}$$

For simplicity, a two-component galactic model will be adopted, consisting of a flat component with $f_1 = f$ and $\beta_1 = \beta$, and a dispersed component with $f_2 = 1 - f$ and $\beta_2 \gg z_{max}$. In the following calculations, a fixed phase interval $\phi_1 = 0.25$ to $\phi_2 = 0.75$ will be used, corresponding to the half of the Sun's time that is spent farthest from the galactic plane. Figure 1 shows the numerical results for different values of f and z_{max}/β.

Unless f is rather large, the expected proportion of encounters far from the galactic plane will not differ significantly from 0.5. Terrestrial evidence suggests that ~20 important encounters have occurred during the past 600 Myr (ref. 2). With $z_{max}/\beta = 1.8$ and $f \sim 1$, an average of 6 encounters out of a total of 20 are expected to have occurred when the Sun was farthest from the galactic plane. On the basis of the binomial distribution, the probability of obtaining $n/N \leqslant 0.3$ as the outcome of $N = 20$ Bernoulli trials with individual success probability $p = 0.5$ is

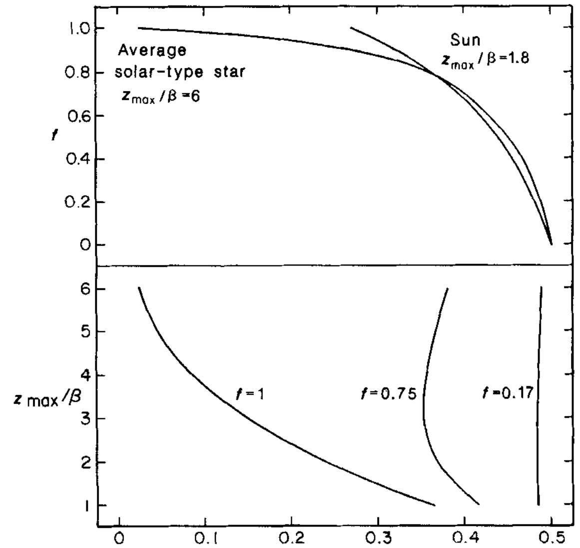

Fig. 1 Expected fraction of the encounters that occur when the Sun is farthest from the galactic plane. This fraction, n/N, is shown separately for the galactic parameters f and z_{max}/β.

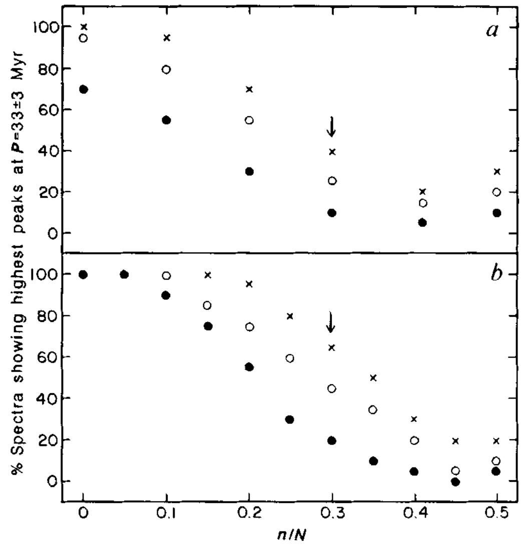

Fig. 2 Percentage of the synthetic power spectra that show one of the three highest peaks at a period of 33 ± 3 Myr. ●, Highest peak alone; ○, the first or second highest peak; ×, case of the first, second or third highest peak. The parameter n/N is the fraction of the encounters that occur when the Sun is farthest from the galactic plane. A small dip in the derived percentages between $n/N = 0.4$ and 0.5 is due to a random statistical fluctuation. *a*, $N = 10$; $t = 0$–297 Myr. *b*, $N = 20$; $t = 0$–594 Myr.

$P = 0.06$. This suggests that f probably has to exceed f_0 for the galactic model to be viable.

To test this hypothesis in a way that also reduces the many assignable parameters to one, the quantity n/N will be specified. This simplification will not significantly bias the statistical outcome of a large number of Monte-Carlo simulations of the galactic effect if the number of simulations is great enough (tests show that this number must be >20). In each simulation, a pseudo-random time series containing N times drawn at random from a time interval $t = 0$ to $t = T$ will be generated with the constraint that n times randomly occupy a broken subseries consisting of alternate sections of length $P_{1/2}/2$ while $N - n$ times randomly occupy the subseries that is complementary to the first. The complete time series will be formally searched for significant periods in the same way that was used for the observed time series, by computing a power spectrum for a range of trial periods and then picking out the highest spectral peaks[2]. In effect, the theoretical problem has been reduced to specifying the three dimensionless quantities n/N, N and $T/P_{1/2}$, the last being the total number of assumed underlying cycles. In what follows, an explicit value of $P_{1/2} = 33$ Myr, with trial periods of 16–100 Myr, will be adopted. Two typical cases, $N = 10$ for $t = 0$–297 Myr and $N = 20$ for $t = 0$–594 Myr, will be considered, while, for each assigned value of n/N, 40 Monte-Carlo simulations will be made.

Figure 2 shows the results, presented in terms of the percentage of the synthesized spectra at each value of n/N that display the highest peak, or one of the two highest peaks, or one of the three highest peaks at a period of $P = 33 \pm 3$ Myr. Spectra that have already been generated for the observed time series of impact craters (and also of geological tectonic phenomena that might be related to impacts) indicate that a significant period of 33 ± 3 Myr usually shows up as the first or second highest peak[2]. Among the synthetic spectra with the observationally favoured value of $n/N = 0.3$, a signal this strong appears in 50% of the spectra for $N = 20$. (The *a posteriori* probability of detection, of course, can be much higher[2].) Tests with periodic time series show that dephasing of a cycle by artificially introducing noise (corresponding to, say, a deflecting encounter of the Sun with a giant molecular cloud) makes only a few per cent difference in the derived best period and best value of the most recent epoch; even several abrupt phase shifts can be safely tolerated.

In an independent investigation of the galactic model, Thaddeus and Chanan[5] applied standard Fourier analysis to many comparable pseudo-random time series. They adopted a gaussian z distribution for the flat component (molecular clouds) and used $z_{max}/z_{1/2} = 72/85 = 0.85$, thus obtaining a signal-to-noise ratio of 0.45 for $N = 9$. Their adopted value of $z_{1/2} = 85$ pc was based on $R_0 = 10$ kpc (making $z_{1/2}$ too large by 15%) and was weighted heavily by a flare of molecular material out of the galactic plane in the Carina spiral arm. This flare is seen also in OB stars, which, outside the flare and close to the solar circle, show $\langle|z|\rangle = 38$ pc (ref. 75), corresponding to only $z_{1/2} = 56$ pc if a gaussian distribution is assumed. Thaddeus and Chanan also adopted $z_{max} = 72$ pc, which was based on a value of $Z_\odot = 7.4$ km s^{-1} (refs 8, 35, 76) derived from data now over 25 yr old. By taking averages of more recent data obtained by many different authors and thus reducing the effect of accidental errors, the present analysis of the observational material suggests that $z_{max}/z_{1/2} = 88/60 = 1.5$. This yields a signal-to-noise ratio of 1.5 for $N = 20$, according to supplementary calculations presented by Thaddeus and Chanan[5]. Although this may still not be detectable with their method, the method that I have used above is demonstrably successful.

The present method of statistical analysis suggests that a galactic signal is potentially detectable (with a 50% *a priori* probability for detection) in the 600-Myr terrestrial time series if the basic model is accepted as now formulated and the following conditions are met: First, ρ_0 must equal $\sim 0.2\ M_\odot$ pc^{-3} to explain the ~32-Myr terrestrial periodicity. This value of ρ_0 accords with the best astronomical evidence and implies that about half of the matter in the galactic disk near the solar circle is unseen. Second, the Solar System's vertical orbit must reach far enough above and below the galactic plane to outdistance most of the matter that is most significantly perturbing the Sun's halo of comets. A value of $z_{max}/\beta = 1.8$ appears observationally likely. Third, the main perturbing objects as well as the dominant contributors to the mass in the galactic disk (which may not be the same objects) must more or less uniformly populate both the spiral arms and the inter-arm regions to ensure a stable periodicity as the Sun orbits the galactic centre. (Some density enhancement of the perturbing matter in the major spiral arms, however, is possible and may explain the observed ~260-Myr terrestrial periodicity[2].) Finally, the 'effective' gravitational mass density of the main perturbing objects must exceed their formal spatial mass density in comparison with objects in the dispersed component. Interstellar clouds with intermediate to large masses are likely to be the most important perturbers. It is, therefore, reasonable to conclude that the proposed[1] galactic model of terrestrial catastrophism is still viable and can be observationally and theoretically tested in various ways.

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Note added in proof: Bahcall and Bahcall[77] recently studied the Sun's z motion in the framework of a more sophisticated galactic model. They confirmed the approximate validity of the harmonic oscillator model adopted here and by Thaddeus and Chanan[5]. For their applications, however, they used values of $Z_{\odot}$ that are smaller than the best estimate derived here.

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Concordant 3,676 Myr U–Pb formation age for the Kodaikanal iron meteorite

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The Kodaikanal iron meteorite contains evidence of intensive chemical activity which, according to Rb–Sr studies[1], occurred ~800 Myr after the formation of the Solar System. Here we report the results of U–Pb isotope analyses on a silicate inclusion from Kodaikanal. Leaching experiments on the two major phases, clinopyroxene (CPX) and alkali-rich glass, indicate a contamination by terrestrial Pb attributable to previous curatorial cutting of this iron meteorite. The leached minerals define concordant U–Pb ages that validate the precise Pb–Pb age of 3,676±3 Myr. These data are consistant with Rb–Sr age determinations[1]. The absence of initial Pb indicates a fast cooling of the silicate material. This has already been established for the metal phase, and a collisional origin for Kodaikanal is favoured.

Kodaikanal is the first iron meteorite with silicate inclusions in which K-feldspar was observed[2,3]. Rb–Sr isotope analyses of these inclusions show that different mineral fractions and separate inclusions are highly enriched in alkalis and that they lie on one isochron, defining an age of 3,800±100 Myr ($\lambda_{Rb} = 1.39 \times 10^{-11}\ yr^{-1}$) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71±0.02 (ref. 1). This study revealed that the observed age is not simply the result of reheating and reworking of material which had been originally formed at 4,500 Myr, but that it represents silicate formation by chemical differentiation from a reservoir with a much lower (possibly chondritic) Rb/Sr ratio. This study pointed out the occurrence of intensive chemical activity in/on a small planetary body at a time far beyond the early formation of solid objects in the Solar System. Two alternative energy sources which support this late chemical process were proposed: thermal energy stored in a planetary body of 200–500 km radius or kinetic energy dissipated as heat during a collision at 3,800 Myr. Rare gas studies indicate a K–Ar age of 3,500±100 Myr for two silicate inclusions[4] and an exposure age for the Kodaikanal meteorite of 10–20 Myr (ref. 5), which is rather short compared with other iron meteorites. Chemical and mineralogical studies[6,7] specify the formation of the Kodaikanal material as a mixture of silicates and metal which formed independently. The high degree of chemical and mineralogical fractionation of the inclusions seems to contradict a core origin[8] but could be explained in a model where differentiated stony material is taken up by an iron melt which was produced in the near crustal portion of a parent body. This mixing event includes: (1) equilibration of the silicates at high temperature and low pressure; (2) fast dispersion of the silicates in the metal phase, which is melted or highly plastic; (3) rapid chilling of the mixture; and (4) subsequent intense deformation. This favours a collisional origin for the Kodaikanal meteorite.

The purpose of our U–Pb study of Kodaikanal was to evaluate the usefulness of this method for dating silicate inclusions of iron meteorites and to help establish the chemical signature of the 3,800-Myr event.

We restricted our study to a single inclusion given the large number of preliminary analyses which are necessary during sample preparation. The inclusion originates from Kodaikanal sclice number 1159 from the Paris Natural History Museum (P2 in ref. 6).

The inclusion, which was visible at the surface, was extracted with a tungsten carbide chisel. The two major phases, clinopyroxene (20 vol. %) and alkali-rich glass (80 vol. %) were separated with tweezers under a binocular microscope. To evaluate and to eliminate Pb contamination, the clinopyroxene fraction CPX (7.6 mg) and the glass fraction which was divided in two aliquots, GL1 (11.0 mg) and GL2 (6.6 mg) were leached